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6. AUTHOR(S)
Matthew R. Gilpin, David B. Scharfe, Marcus P. Young, and Anthony P. Pancotti

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AFRL/RZSA
10 E. Saturn Blvd.
Edwards AFB CA 93524-7680

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Latent heat thermal energy storage systems promise nearly constant temperature operation and greater energy storage densities than sensible heat energy storage systems, but they are not yet commonly used in practice due to limitations in material degradation and heat transfer rates. Systems employing particular elemental materials with high melting temperatures appear to overcome these limitations, yielding significant performance increases, particularly in bimodal (thermal and electric) solar thermal power systems. A review of candidate materials has concluded that silicon is an excellent candidate for near term, moderate performance systems, while boron, the primary focus of this paper, is an excellent candidate material for future high-temperature, high performance systems suitable for advanced microsatellite solar thermal propulsion and power systems. General considerations for systems employing such materials have been identified, the required support technologies, including high temperature thermal insulation and thermal to electric power conversion, have been evaluated, and a preliminary design for a general system has been completed. Several potential applications have been identified for this technology; one of them, a solar thermal power and propulsion unit for a 100kg microsatellite, will be described in this paper. The preliminary analysis indicates that such a bimodal system would enable large ΔV maneuvers for 100kg microsatellites while also producing the required electrical power. A solar thermal test facility for further evaluating such systems is described along with initial results from the build-up phase of the facility.

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Molten Boron Phase-Change Thermal Energy Storage: Containment and Applicability to Microsatellites

Matthew R. Gilpin[1]
University of Southern California, Los Angeles, CA, 90089

David B. Scharfe[2]
ERC Inc., Edwards AFB, CA, 93524

Marcus P. Young[3]
Air Force Research Lab, Edwards AFB, CA, 93524

and

Anthony P. Pancotti[4]
MSNW, Redmond, WA 98052

Latent heat thermal energy storage systems promise nearly constant temperature operation and greater energy storage densities than sensible heat energy storage systems, but they are not yet commonly used in practice due to limitations in material degradation and heat transfer rates. Systems employing particular elemental materials with high melting temperatures appear to overcome these limitations, yielding significant performance increases, particularly in bimodal (thermal and electric) solar thermal power systems. A review of candidate materials has concluded that silicon is an excellent candidate for near term, moderate performance systems, while boron, the primary focus of this paper, is an excellent candidate material for future high-temperature, high performance systems suitable for advanced microsatellite solar thermal propulsion and power systems. General considerations for systems employing such materials have been identified, the required support technologies, including high temperature thermal insulation and thermal to electric power conversion, have been evaluated, and a preliminary design for a general system has been completed. Several potential applications have been identified for this technology; one of them, a solar thermal power and propulsion unit for a 100kg microsatellite, will be described in this paper. The preliminary analysis indicates that such a bimodal system would enable large ΔV maneuvers for 100kg microsatellites while also producing the required electrical power. A solar thermal test facility for further evaluating such systems is described along with initial results from the build-up phase of the facility.

I. Introduction

Solar thermal energy systems convert the energy contained in sunlight to electrical energy, to direct thermal heating, or both. Terrestrial solar thermal systems can provide point-of-use electricity and hot water while spacecraft solar thermal systems can provide both propulsion and electrical power. Such systems fundamentally

[1] Graduate Student, University of Southern California, Los Angeles, CA 90089, AIAA Member.
[2] Research Scientist, ERC Inc., 10 E. Saturn Blvd, Edwards AFB, CA 93524, AIAA Member.
[3] Program Manager, AFRL, 10 E. Saturn Blvd, Edwards AFB, CA 93524, AIAA Member.
[4] Research Scientist, MSNW LLC., 8551 154th Ave., Redmond, WA 98052, AIAA Member.

require some form of energy storage to maintain operation during periods with insufficient illumination. Terrestrial systems require storage for both short term dips in power production due to cloud cover and longer term, higher capacity storage for overnight operation. Space systems require storage to maintain operation during the eclipse period of the orbit. Eclipse frequency and period depend heavily on the particular orbit, with LEO being the most demanding on storage systems because of its frequency (~every 90 minutes), duration (~40 minutes), and total number of cycles during a mission (~50,000). The simplest and most cost effective storage philosophy is to store the collected energy thermally before it is converted to multi-use electrical energy or transferred for thermal (i.e. propulsive) use. Terrestrial systems are beginning to use thermal energy storage and the primary focus is on sensible heat thermal energy storage systems. The current generation of sensible heat energy storage techniques is fundamentally incapable of meeting the requirements of space-based solar thermal systems where energy storage density plays a dominant role. Advanced thermal storage systems based on very high temperature solid materials such as boron carbide or graphite have been investigated for use on spacecraft and are predicted to be viable for large-scale satellites.[1] Sensible heat energy storage systems, even high performance systems, fundamentally require large operating temperature changes and are unable to match the energy density of latent heat energy storage systems.

Latent heat thermal energy storage systems typically provide significantly higher stored energy density, but their application has been limited due primarily to material stability problems, which limits a system's useful life, and low thermal conductivity, which limits the heat transfer rates into, within, and out of the storage material. There are, however, elemental materials that have thermal conductivities that are 10 to 100 times higher than traditional phase change materials and that have no material stability problems. These materials have melting points that are much higher than traditional phase change materials. Systems employing these materials will be fundamentally different than the molten salt based solar thermal plants that use Brayton cycle energy conversion. Operating at higher temperatures can potentially lead to higher conversion efficiencies, but will also require high temperature insulation and careful designs to allow long-term operation at very high temperatures. Ground tests of a bimodal solar thermal system (intended for large-scale spacecraft applications) that uses sensible heat energy storage have demonstrated the basic operation of a similar system with many of the required components at the required high temperatures.[2] The bimodal solar thermal system for microsatellites will, however, require several key modifications to the system, the most important of which is operating with a high temperature elemental phase change energy storage system. The bimodal solar thermal microsatellite system described here may also have application to terrestrial systems if the design is modified to optimize for minimum cost instead of minimum mass.

A. Sensible Heat Thermal Energy Storage Systems

Storage systems that use sensible heat as the means of thermal energy storage operate on the principle of raising the temperature of a material with a high specific heat. These systems fundamentally require sizeable temperature changes (100's of K) during a charge-discharge cycle to achieve useable energy densities, which leads to suboptimal electrical energy conversion and decreased lifetime due to repeated thermal cycling. Thermal cycling concerns can be partially mitigated by systems that regulate the stored energy through mass addition rather than by changing the temperature of a set volume of material.

Industrial-scale terrestrial solar thermal power systems are currently in operation. They are cost competitive with solar photovoltaic systems and may outcompete them when storage is included. These systems are typically too heavy, too complicated, and operate at too low a temperature for spacecraft solar thermal systems. The current material of choice for terrestrial systems is a molten salt mixture of 60% sodium nitrate and 40% potassium nitrate. It is non-flammable, non-toxic, and there is significant experience with the material in industry.[3] However, the mixture has neither the required high useful temperature nor the high energy density required for the microsatellite solar thermal propulsion and power system described here. Table 1 summarizes relevant physical properties for traditional terrestrial solar thermal systems.

Table 1. Relevant Properties of Traditional Sensible Heat Energy Storage Materials

Material	$T_{operation}$ [K]	$E/(\Delta Tm_{material})$ [kJ/kgK]	Notes
[60% $NaNO_3$ + 40% KNO_3][3]	560-840	1.5	ΔT = 280K $\rightarrow$ 0.42MJ/kg
Brick[4]	300-1450	0.84	ΔT = 1050K $\rightarrow$ 0.96MJ/kg
Concrete[4]	300-1250	0.88	ΔT = 1050K $\rightarrow$ .84MJ/kg
Water[4]	300-373	4.2	ΔT = 73K $\rightarrow$ 0.31MJ/kg

Table 2. Relevant Properties for Candidate High Temperature Sensible Heat Storage Materials[1]

Material	T_{melt} [K]	$c_{p,s}$ [kJ/kgK]	$\Delta E/m_{2000\text{-}2600K}$ [MJ/kg]	ΔH_{fus} [MJ/kg]
Carbon	*3923*	*2.09*	*1.25*	---
Tungsten	3643	0.134	0.0804	0.284
Rhenium	3453	0.15	0.09	0.325
Boron Nitride	3273	1.99	1.194	---
BeO	3010	2.43	1.458	3.41
Molybdenum	2890	0.255	0.153	0.391
Silicon Carbide	2818	1.47	0.882	---
B_4C	*2700*	*2.51*	*1.506*	*7.963*
Boron	2570	2.93	[redacted]	4.65
Al_2O_3	2322	1.36	[redacted]	4.58
Silicon Nitride	2173	1.13	[redacted]	---
Silicon	1685	0.963	[redacted]	1.8

The primary application discussed in this paper, a bimodal solar thermal system for microsatellites, will likely require both significantly higher temperature operation and higher energy densities than the traditional sensible heat energy storage materials provide. Materials with melting points significantly above the planned operation temperature were reviewed to determine the ultimate long-term potential of high temperature sensible heat storage materials. Systems using solid materials are significantly simpler, so only materials with melting temperatures above the envisioned applications were evaluated. Table 2 summarizes the relevant properties for candidate high temperature sensible heat energy storage materials. The materials below the dashed line are applicable for phase change applications and other support roles, and are included for completeness.

Previous work on sensible heat thermal energy storage for spacecraft applications has determined that boron carbide and carbon were optimum materials for the applications studied.[1] These two materials will be chosen for later comparisons with high temperature latent heat phase change materials. The performance of these materials is ultimately limited by the allowable temperature change defined by mission requirements. Larger temperature changes will reduce the power conversion efficiency and place additional stress on materials due to temperature cycling. High performance materials are unlikely to compete with molten boron phase change energy storage for spacecraft applications, but may compete with lower performance systems, such as molten silicon, for terrestrial applications.

B. Latent Heat Thermal Energy Storage Systems

Latent heat thermal energy storage systems operate on the principle of energy storage due to the phase change of a material (typically solid to liquid). Significant efforts have been spent studying candidate materials for terrestrial systems, but they have not yet found widespread application. Thousands of materials have been evaluated for this application, but they can be divided into three broad classes, which are listed in Table 3 along with some characteristic properties.[5]

Traditional phase change materials typically have energy densities and thermal conductivities about one order of magnitude below requirements, melt at temperatures much too low for spacecraft applications, and can decompose after repeated cycling. There are higher temperature latent heat materials that have been investigated, but, as shown in Table 4, they are still insufficient for microspacecraft bimodal solar thermal systems.

Traditional latent heat thermal energy storage materials have energy storage densities below roughly 0.5 MJ/kg, a number typical of electrochemical battery-based energy storage systems. Significant improvements beyond this

Table 3. Relevant Properties for Typical Phase Change Materials

Class	ΔH_{fus} [MJ/kg]	T_{melt} [K]	k_{th} [W/mK]
Paraffin Wax[5]	0.072 – 0.214	317 – 379	0.19 – 0.75
Fatty Acids[5]	0.045 – 0.210	268 – 344	0.14 – 0.17
Hydrated Salts[6]	0.115 – 0.492	281 – 1170	0.46 – 5.0

Table 4. Traditional Phase-Change Thermal Storage Media with Highest Melting Points[6]

Compound	Melting Temp [K]	Heat of fusion [kJ/kg]
$MgCl_2$	987	452
45.8%LiF + 54.2%MgF_2	1019	Not Available
NaCl	1073	492
53.6%NaF + 28.6%MgF_2 + 17.8%KF	1082	Not Available
66.9%NaF + 33.1%MgF_2	1105	Not Available
Na_2CO3	1127	275.7
Salt Ceramics $NaCO_3$-$BaCO_3$/MgO	773-1123	415.4
KF	1130	452
K_2CO_3	1170	235.8

capacity would be required for phase change materials to be advantageous in space. High temperature elemental materials, as discussed later, may provide the required improvements.

C. Relevant Thermal Energy Storage Work

There has been a broad range of solar thermal work investigating terrestrial and spacecraft applications. A brief description of only the most relevant terrestrial and proposed space applications is provided below.

1. Terrestrial Applications

There have been significant efforts in the field of solar thermal terrestrial power production. Industrial scale solar thermal power plants have been in operation for decades, but solar thermal plants with thermal energy storage have only recently come on line. For example, in 2009 the Solar Millennium Andasol solar power station came on line and has a capacity for up to 7.5 hours of full load thermal energy storage in a molten salt.[7] As indicated earlier, however, the technology employed in these systems is fundamentally incapable of providing the performance required for a small-scale space-based system.

There have been two solar thermophotovoltaic research efforts that are particularly applicable to the current work. The first research effort was conducted by McDonnell Douglas Corporation in the late 1990s.[8,9] In the effort, they designed a solar thermophotovoltaic power system that also incorporated a molten silicon thermal energy storage system. A prototype system, without thermal energy storage, was tested up to the required temperatures, 1473 K, and was operated under illumination for 550 hours. It was concluded that molten silicon systems based systems could operate at total electrical system efficiencies of greater than 25%, with 40% possible in the far term. The research group also proposed a similar system for space-based applications and initial estimates indicated that it could provide a very lightweight power system for satellites.[10] Although many of the required components were demonstrated, effective thermal energy storage was never demonstrated, the design didn't include bimodal operation, and a long-term demonstration of the system at high temperatures was still required.

A similar bimodal terrestrial solar thermophotovoltaic system developed by Edtek has successfully demonstrated electrical power and hot water generation.[11] The system uses a combination of concentrated sunlight and a natural gas burner to heat a silicon carbide emitter. The emitter is partly surrounded by an optical system consisting of a selective filter, infrared optics, and thermophotovoltaic cells. A constant flow of water is used to cool the thermophotovoltaic cells, which provides a useful hot water output. The complete system converts approximately 25% of the incoming solar energy into electricity, and 50% of the energy is held in the heated water, providing a total system efficiency of 75%. The system lacked any thermal energy storage, but did demonstrate most of the remaining components and high efficiency, high power density operation. Space-based systems would also not be able to make use of the heated cooling water.

2. Space Applications

The concept of solar thermal space propulsion systems has roots in the early work of Krafft Ericke's Solar Powered Spaceship in 1956, and continuous progress towards space-based solar thermal systems has been made since then. The work most relevant to the current paper is that of the AFRL/NASA work in the late 1990s on the Integrated Solar Upper Stage (ISUS) program, which culminated in a bimodal system for large satellites with a TRL of 6.[12,13] The program developed a bimodal solar thermal system that was meant to first provide a large ΔV propulsion system for maneuvers like LEO to GEO transfers and then provide continuous electrical power to the spacecraft when it was in its final orbit. The system used a rhenium-coated graphite thermal absorber that provided some amount of sensible thermal energy storage. The thermal to electrical energy conversion was accomplished using a thermionic system. The propulsion systems used a highly effective narrow tube heat exchanger system to heat the hydrogen propellant before expanding it out of a nozzle. A specific impulse of approximately 750 seconds was achieved in ground tests, but the system was never flight-tested. The primary limitation for the system was the large storage volume required for the hydrogen propellant. The receiver/absorber/converter (RAC) system is similar to what is envisioned for the microsatellite bimodal system described here, but it would require several changes: it must be shrunk to the relevant physical dimensions, it must incorporate latent heat energy storage material for improved energy storage, and it should include throttling of the electrical energy output. A schematic of a new RAC incorporating the required changes is described later.

While a large variety of solar thermal propulsion systems for microsatellites have been proposed and studied in ground tests and simulations (e.g.: References 1, 14 - 19), no solar thermal rockets, much less those intended for microsatellites, have ever been flown.[20] The literature does note that STP, if implemented correctly on a microsatellite, would represent a significant enhancement to the microsatellite platform. As noted by Kennedy[1], microsatellites are generally launched as secondary payloads accompanying higher-budget missions; as such, microsatellites are typically placed in sub-optimal orbits for their own mission goals. Providing a microsatellite with an STP system could allow a 1.5-2 km/s delta-V, allowing the satellite to reposition to an optimal orbit when starting from a wide variety of initial orbits. Additionally, by providing a delta V of several hundred m/s or larger, the microsatellite operating regime would be widened to include Geosynchronous Transfer Orbit (GTO) to Geosynchronous Earth Orbit (GEO), lunar orbit insertion, highly eccentric orbits for observation and analysis, LaGrange point and Earth-trailing orbiters, and even Earth escape.[1] Even end-of-life deorbiting of microsatellites can be economical with an STP system.[15]

When mission studies or systems analyses of solar thermal propulsion systems for microsatellites are performed, however, compromises to the system performance are allowed due to the requirements of solar flux. Even those studies that investigate utilizing a thermal storage system rely only on sensible heat. In these cases, the thermal storage system implemented, whether it be in heated graphite[1], boron carbide[1], boron nitride[1] or some other refractory material, is only used to augment the steady-state thrust capabilities of the system. In some cases, this requires "charging" the thermal system for several times longer than the actual burn time of the STP rocket[1]; this may indicate a solar collector that is perhaps too small for the utmost in performance and response time. As a result, the proposed systems generally end up with a much slower orbit transfer capability than would be possible with a more advanced system of solar collection and thermal storage.

Nonetheless, even in small-scale systems intended for microsatellites, sunlight concentration ratios in excess of 10,000:1 have been achieved[15,16] from very lightweight collection systems weighing under 200 g/m^2;[15] absorber temperatures approaching 3000 K have been achieved[17]. Hitting the instantaneous performance requirements of an STP system is relatively straight forward, and augmenting that performance via reliable, high-performance thermal storage and thermal-electric conversion is where significant advances should be made.

3. Summary

The individual components required beyond the phase change material and absorber/converter are all essentially developed, proven technologies. It is still required to show that the high temperature phase change material can be incorporated into the system and that individual technologies that have been previously validated can be integrated into a complete, optimized system. It would also be useful to show successful long-term operation as well as efficient throttling of the infrared flux to the thermophotovoltaics to provide varied electrical output (which would eliminate the need for heavy or expensive batteries).

II. Potential Applications

A highly efficient and versatile means of energy storage could have a wide range of potential applications. A highly compact, high-temperature solar collection system including thermal storage and electrical conversion would be ideal for significantly enhancing the performance of microsatellite systems in a variety of missions. A similar system, or perhaps just one aspect of it (i.e.: thermal storage without an attached collection system) could also be designed and optimized for the necessary cost, size, and performance parameters required for various other uses. Therefore, the concepts of solar collection and thermal storage combined with electrical conversion should be evaluated for systems ranging from terrestrial power systems of various scales to automobiles, aircraft, and near-space vehicles. A brief discussion of various potential applications for a high-performance latent heat system is provided below.

A. Microsatellite Solar Thermal Propulsion/Power With Thermal Energy Storage

Light-weight (100 kg class and smaller) microsatellites, combined with miniaturized spacecraft components, are a well-established technology proven to reduce the costs and enhance the capabilities of certain space missions. Despite the many advantages that microsatellites can bring to a variety of mission scenarios, microsatellite capabilities in terms of the ultimate velocity increment (Delta V) available for station keeping, orbit transfers, and other maneuvers have been viewed as somewhat limited.

A recent review of propulsion technologies has indicated the strong potential performance offered by Solar Thermal Propulsion (STP) in microsatellite systems.[21] In a typical STP system, a solar concentrator is used to focus sunlight onto a thermal energy collector, which directly heats a non-reacting propellant gas before it is accelerated to produce thrust. Analysis of under-development STP systems indicates that these systems should be able to fill the performance gap between relatively inefficient high-thrust chemical rockets and the more efficient but very low thrust offered by low-power electric propulsion systems intended for microsatellites[1,21]; in this way, STP may provide the high Delta V and fast response time required to usher microsatellites into an entirely new class of high performance missions.

Traditionally, however, STP has been limited due to the requirement for solar illumination of the collector during times when propulsion is needed; this creates apparent difficulties with respect to the satellite orientation and timing of propulsive maneuvers. Typical systems are further limited by fluctuations in the temperature of the collector during operation, which would create imprecise thrust performance. Employing an STP system also requires the use of a large solar concentration and collection system, while more traditional propulsion systems can share the power generated by photovoltaic (PV) arrays that are required by the payload. Issues related to satellite pointing can be solved by decoupling the satellite body from the solar concentrator through the use of fiber optic collection and transmission of concentrated sunlight.[22,23] Adding to that a system with phase-change thermal storage capabilities and a means of thermal-electric power generation can additionally provide a means to produce relatively isothermal thrust augmentation, even during times of eclipse, while simultaneously eliminating the need for a traditional power system (PV arrays and batteries) on board the craft. In this way, a well-designed system could potentially provide significant performance and mass advantages for a number of potential microsatellite missions.

With the above in mind, the work detailed in this paper to develop a thermal storage system with means of extracting both electrical and thermal power, has direct applications to advanced microsatellite systems intended for low Earth orbit (LEO). The system envisioned for a microsatellite would include a large concentrating dish (or several small dishes) to collect sunlight and focus it onto a fiber optic pathway. The fiber optics would carry the solar energy to the thermal storage medium, where it would be used to produce heat and melt the medium. The latent heat stored within the molten material would be preserved via advanced insulation, but could be extracted for use as a means to heat propellant and produce thrust, or converted to electricity for directly powering other satellite systems. While a scaled-up version of the system would apply equally well to a full-scale satellite, it is the field of microsatellites that would benefit the most from this advanced energy system.

The most direct competition to the proposed combined propulsion and power system would be conventional satellites equipped with either chemical (hydrazine) rockets producing several Newtons of thrust at ~200 seconds of Isp or electrostatic rockets with a high Isp (>1000s) and low thrust (milliNewtons). With this in mind, a set of goals has been targeted for the proposed system, as listed in Table 5.

The first parameter listed in Table 5 is the operating temperature. Data in the literature indicates that the optimal temperature for operating an ammonia-fueled solar thermal rocket is 2500 K, which produces an Isp in excess of 400 seconds.[17,23] However, even at a temperature of only 1400 K, the Isp for such a system would be 300 seconds, which is a marked improvement over small-scale chemical thrusters.

Comparing the energy and power densities to conventional systems is somewhat difficult due to the differing nature of a standard all-electric system and the dual-use nature of the combined electrical and thermal energy system described here. Therefore, the energy density target is related to the means of energy storage only: the insulated thermal storage system described here, as compared to standard batteries in traditional satellites. Traditional off-the-shelf batteries achieve an energy density of approximately 500 kJ/kg. Therefore, a step to 750 kJ/kg would be a noteworthy improvement, and going to several thousand kJ/kg would be a revolutionary change. The power density comparison is further complicated by the fact that the balance of electrical versus thermal (propulsive) power used would vary by mission, and that converting solar flux to thermal energy is generally much more efficient than converting to electrical. As a starting point, however, a target of 100 W/kg is listed as a typical battery power density for comparison to the thermal storage system. State of the art solar panels for space use currently achieve 80 W/kg, with NASA targeting 140 W/kg during 2012, and a long-term goal for power collection of 250 W/kg.[24] This number would best be compared to the power density of the means of collection and electric conversion of the

Table 5. Targeted Performance Parameters for Microsatellite Solar Thermal Power and Propulsion System

Parameter	Ideal	Minimum Acceptable
Operating Temperature	2500 K	1400 K
Specific Energy Density (Storage only)	>2500 kJ/kg	>750 kJ/kg
Specific Power Density (Storage Only)	> 100 W/kg	100 W/kg
Specific Power Density (Collection and conversion only)	> 200 W/kg	150 W/kg
Power loss per cycle	<5%	25%
Cycle Life	>1,000	50

proposed system, although the value of utilizing the stored thermal energy directly for propulsion would be clouded by this comparison.

Due to the nature of storing thermal energy, a certain amount will be lost through the insulating material. There must be a trade-off made between the mass and volume required for the extra insulation and the benefit of losing less of the stored power. Assuming that the thermal energy storage system has a notably larger energy storage density than a battery, however, fairly significant energy loss may be acceptable. As a starting point, allowing 25% of the stored energy to be lost during one cycle (i.e., orbital period) of the satellite is the minimum target.

Finally, most energy storage systems have a limited total cycle life, and it is likely that a thermal storage system operating at very high temperatures would degrade with time due to physical or chemical changes. Assuming that the proposed system was targeted at a satellite which required a rapidly delivered, very large Delta V, producing large amounts of thrust from the STP system over a few tens of orbits begins to make the thermal storage system look interesting. For a more long duration mission, many thousands of cycles would be ideal.

Assuming that a thermal-storage system meeting these requirements can be designed and coupled with an STP system that is capable of producing something on the order of Newtons of thrust, a microsatellite capable of a Delta V of several hundred meters or even kilometers per second would be achievable, and the response time would be on the order of hours; this combination would not be achievable with more typical propulsion systems.

B. Additional Potential Applications

An advanced energy storage and conversion system has the potential to revolutionize a variety of applications. While the unique advantages of such a system might not suit a given sector, it is prudent to analyze the possible benefits, detractions, and areas for further improvement that may exist.

One potential area in which a thermal energy storage system may provide distinct benefits is in remote or off-grid terrestrial power generation. For a remote site, such as a permanent homestead or a temporary encampment, generating power for necessary operations is always a concern. For a mobile group, the weight of equipment that must be hauled in to generate power would be a key factor in determining a system's usefulness. Traditionally, remote generation and storage might be accomplished by utilizing either a photovoltaic system with batteries for electrical storage, a combustion-based electrical generator, or via a "hybrid" generator with battery-based electrical storage to improve efficiency. Whether the installation was temporary or permanent, there would be significant cost savings relative to PV if a thermal collection system were used; additionally, the use of a thermal system would have the added output of efficiently converted heat for use in hot water, space heating, or a variety of other applications. Solar power generation, whether based on thermal storage or traditional PV, has the advantage of being entirely self contained once installed; combustion-based generators require periodic refueling from external supply lines. In the case of a temporary or mobile system, significant mass savings could be achieved by using in-situ materials in a thermal storage system; silica-based sand, for example, has a moderate energy storage capacity when melted, and could theoretically be added to a system on-site as the phase change material. For a more permanent installation, a higher performance storage material would likely be advantageous at a nominal additional cost. Depending on specific needs, the thermal energy conversion from a small-scale remote power system could be done via thermophotovoltaics or by flowing water through the system and operating a steam turbine cycle. For general, small-scale use, a thermal storage system could be optimized for temperatures ideal for TPV conversion, with a hot temperature of at least 1200 K; if steam-based generation was utilized instead, this temperature could likely be lower. The thermal energy output from the system would need to at least pre-heat a hot water supply (310 K), but would ideally heat the water to a peak useful temperature of 335 K.

An advanced thermal energy storage system may also be useful for larger scale power generation, with applications to solar thermal power plants with energy storage for load balancing and output during times of decreased or absent solar flux. In this case, cost, simplicity, and long-term reliability would be the top concern. Typical solar thermal plants utilize steam turbines to generate power; it is likely that such turbines would be highly efficient, and it would be most simple to couple the thermal storage to this system for electrical generation rather than using additional TPV conversion. Temperature requirements would be in line with ideal steam generation temperatures.

For mobile systems such as automobiles, trains, and aircraft, the available surface area for power generation would be minimal due to the need to avoid drag forces and retain useful volumes for transporting humans or cargo. Additionally, while the thermal storage capacity of an advanced system could be notably larger than the capacity of a battery system, the liquid fuels traditionally used for these applications still have an order of magnitude larger energy density. Even comparisons to batteries would not likely show an advantage for a thermal storage system that was pre-charged with heat before travel; high performance vehicles would not be able to make use of both an electrical and a thermal output, and the relatively inefficient conversion to electric power would be taking place on-board the moving vehicle, resulting in the need to carry a significant weight penalty and negating the apparent energy density benefit relative to traditional electrochemical batteries.

On the other hand, inflatable or dirigible crafts operating at low altitudes up through near-space may benefit significantly from a thermal-based power system. While costs may preclude covering the surface of such a craft with photovoltaics, a transparent buoyant structure could be shaped and coated to produce a concentrating reflector at minimal cost. The concentrated solar light could be used directly to produce electrical power from concentrated PV or TPV, while producing excess heat for use in augmenting a propulsion system. Adding thermal storage to a system that would need to operate at night could provide further mission flexibility; in this case, a system with a high energy density (low mass) would likely be ideal.

There also may be space-based applications beyond microsatellites. Due to the nature of radiation, thermal storage, and insulation, shrinking a system down to nanosatellite or picosatellite scales would be a much more difficult prospect. However, larger scale satellites may benefit from a scaled-up version of a microsatellite system, with the added benefit of requiring less insulating mass relative to the mass of phase change material (keeping the insulation at the same thickness, but on a larger volume of PCM). As there already a variety of high performance propulsion system for larger satellites, there may be a smaller niche of missions for which a thermal power and propulsion system would show clear benefits.

III. High Temperature Latent Heat Energy Storage Systems

The nominal design for the bimodal solar thermal power and propulsion system described here was constructed by first evaluating each component of the system individually. The primary considerations for each component were identified and used to evaluate candidate materials and methods. The best candidates for each component were then assembled into a preliminary design for the receiver/absorber/converter (RAC) design. A modeling effort to optimize the preliminary configuration is underway.

A. High Temperature Phase Change Material

There are numerous considerations when choosing a high-temperature phase change material for the solar thermal power and propulsion system. Table 6 lists the most important considerations that were assembled from previous material reviews and from the early analysis in the present work. The first two properties, melting temperature and energy density, are critical enabling considerations, while the others also play a strong role.

A thorough search was conducted for phase change materials that met the melting temperature and energy density requirements. Table 7 shows the most promising materials identified during the investigation. Two materials were chosen for further evaluation in the current project: silicon and boron. Boron has the highest energy density (4.6MJ/kg) and a melting temperature that could yield higher specific impulses and a high electrical flux density, but there has been limited research into using the material. Additionally, operating at high temperatures in a very compact geometry places extreme requirements on the required insulation. Silicon, on the other hand, has lower potential performance, but would operate at conditions that are readily achievable and its compatibility has been well studied by the semiconductor industry. Silicon is viewed as the near-term material with strong application in terrestrial systems, while boron is viewed as the far term high-performance material for microsatellite solar thermal systems. The low cost of metallurgical grade silicon ($1.70/kg, which translates to $0.95/MJ) also makes it an attractive candidate for terrestrial thermal energy storage systems.

Table 6. High Temperature Phase Change Material Considerations

High-T Phase Change Material Consideration
- Properly Matched Melting Temperature.
- High Energy Density.
- Good Material Stability.
- Good Material Compatibility.
- High Thermal Conductivity.
- Low Vapor Pressure at Melting Temperature.
- Small Volume Change During Transition.
- High Emissivity.

Table 7. Potential High Temperature Phase Change Materials

Material	Melting Temp [K]	Heat of fusion [kJ/kg]	Thermal Conductivity [W/mK]
Manganese	1519	235	7.8
Magnesium Fluoride	1536	940	
Beryllium	1560	1312	200
Silicon	***1687***	***1785***	***149***
Nickel	1728	298	90.9
Cobalt	1768	272	100
Yttrium	1799	128	17.2
Iron	1811	247	80.4
Scandium	1814	313	15.8
Palladium	1828	157	71.8
SiO_2	1923	188	~1
Lutetium	1925	126	16.4
Titanium	1941	295	21.9
Zirconium	2128	153	22.7
Chromium	2180	403	93.9
Vanadium	2183	422	30.7
Rhodium	2237	258	150
Boron	***2350***	***4600***	***27.4***
Hafnium	2506	152	23.2
Ruthenium	2607	381	117
Iridium	2739	213	147
Niobium	2750	323	53.7
Molybdenum	2896	390	138

B. PCM Containment

The primary added complication for latent heat energy storage, versus sensible heat energy storage, is that the latent heat system will require a storage container made from a material that is chemically compatible and structurally sound at high temperatures. The material must maintain these properties while operating at high temperature for long periods of time, perhaps 10 years or more. The case material adds to the mass of the system and reduces the effective energy storage density. The container material selection is made primarily through compatibility considerations and is therefore completely coupled to the chosen phase change material. Research in the field of the compatibility of molten silicon has been very active in the semiconductor industry, and as a result, a good deal of molten silicon compatibility literature is available. Most of the compatibility research, however, is for high purity samples held for short durations, but this research can still be used to draw some preliminary conclusions. Molten silicon is highly reactive, but both silicon nitride and silicon carbide are proven container materials for at least short-term storage.[24] Molten boron is also highly reactive, and while the literature concerning molten boron compatibility is comparatively limited, there are materials that appear capable of resisting boron attack, as discussed later.

Table 8. High Temperature Insulation Properties

Material	Density [kg/m^3]	T_{melt} [K]	$k_{th,500K}$ [W/mK]	$k_{th,1000K}$ [W/mK]	$k_{th,1500K}$ [W/mK]	$k_{th,2000K}$ [W/mK]	$k_{th,2500K}$ [W/mK]
Aerogel[25]	80	600	0.01				
Fused Silica[26]	2200	1985	1.5	2.1	2.1		
Saphire[27]	4000	2313	20	8	---	---	
Alumina[27]	4000	2345	21	5	5	8	
Boron Carbide[28]	2520	2673	12.5	9	6.5	---	---
Silicon Carbide[29]	3210	3003	120	60	38	28	---
Boron Nitride[27]	3487	3246	37	22	21	19	---
Carbon Bonded Carbon Fiber[30]	180	3273	---	0.4	---	0.9	---
Vacuum [Δx=1cm]	---	---	0.15	0.80	2.39	5.33	10.1

C. High Temperature Insulation

Another critical technology for thermal energy storage and conversion systems is high temperature thermal insulation. Very high temperature thermal insulation materials must meet a long list of exacting requirements, including the ability to withstand the storage temperatures, potentially operate through a number of thermal cycles, be compatible with the other materials involved, and maintain certain structural properties. The present work is focused on systems operating in the temperature range of 1500-2500K. Table 8 lists a select group of common high temperature thermal insulation materials along with a select group of other materials that represent a high-performance material for other select required properties. Aerogel is listed to illustrate the relevant properties for a material that is fully optimized for minimum thermal conductivity. However, it clearly cannot meet the high temperature stability requirement for the applications discussed here. The effective thermal conductivity for blackbody radiation transport across a 1 cm vacuum gap from a surface at the specified temperature to a surface at 300K is also given for reference. It is common for solar thermophotovoltaic systems to use a vacuum gap with low emissivity surfaces on either side as the first insulating layer.[11]

D. Electrical Energy Conversion

There are a wide variety of options for thermal-to-electric systems that operate at a T_h below 1300K and are not mass constrained. Thermoelectrics, AMTEC, and free piston Stirling engines appear fundamentally constrained by T_h and would require significant development efforts to operate at the required T_h for high-temperature thermal-to-electric conversion on spacecraft. Closed Brayton cycle systems that can operate at the required high temperatures are not currently available, but it is likely that with further development the technology may be advanced significantly with carbon-carbon systems. Brayton systems aree, however, typically the most advantageous for large power levels. Thermionic power conversion systems are also typically more advantageous at higher power levels. Nantenna based conversion systems have significant potential, but have yet to achieve any significant fraction of that potential. That leaves thermophotovoltaic systems as the most promising candidate for the near term. TPV systems will be chosen as the representative solution for the discussion to follow. Table 9 provides a summary of the comparison of the states-of-the-art for different energy conversion technologies and comments about the future potential of each technology.

Note that while thermophotovoltaic is much heavier than PV at 15 W/kg, it will likely benefit from the same type of development that has advanced standard PV over the past decade. In 2001, Kessler noted that state of the art 3-junction photovoltaic arrays developed for space weighed in at 15 W/kg.[31] Surprisingly, this is the same value at which TPV systems sit today. Yet, in just over a decade, NASA is targeting nearly 10 times lighter systems (140 W/kg by 2012). It is reasonable to assume, then, that advanced materials and other developments should push TPV systems down to similar levels in a similar time span.

E. Thermal Conversion for Propulsion

While the majority of solar thermal propulsion systems designed do not include a significant means of thermal storage, they can still provide a starting point for the design of the means of heat transfer to the propellant. In typical solar thermal designs, there are two primary means of heating the propellant: either the propellant is heated directly by the concentrated solar light, or the concentrated flux is used to heat an amount of solid material, which then

Table 9. Electrical Energy Conversion Options[32]

Technology	P_{sp} [W/kg]	Efficiency	T_{max} [K]	Comments
Thermoelectric	9.4	6.3%	1273	• Limited temperature operation. • Incremental development OK for P_{sp} & η.
Thermophotovoltaic	15	19%	None	• Long lifetime demonstration required. • Operation in space environment required.
Thermionic	100@1kWe	> 10%	2200	• Baselined for another application at higher power levels.
AMTEC	14	16%	1300	• Unlikely to achieve required temperatures.
Nantenna	???	<1%	None	• Significant uncertainties in all aspects. • Current concern: efficient rectifying diode.
Closed Brayton	---	29%	1700	• Possible to achieve required temperatures. • Mass may be high for low power levels.
Free Piston Stirling	100	35%	1050	• Unlikely to achieve required temperatures. • High performance & long lifetime demonstrated.

transfers heat to the propellant through convective transfer.[18] Typically, the convective heat transfer method can allow a higher flux of higher temperature propellant, resulting in a more efficient and higher performing vehicle. In the proposed research in which significant thermal energy is stored on-board, this effect would be even more dramatic as the radiation emitted from the phase change material would be even less concentrated than the focused solar flux. Therefore, a convective heat transfer method has been selected for the system proposed here.

In systems designed with sensible heat thermal storage, the convective heat transfer is generally accomplished by flowing the propellant either through a tortuous foam of heated particles[1] or through narrow channels within the storage material[33,34]. While these systems rely on the sensible heat capacity of the material as its temperature increases, they can be used as the basis for designing a system with the high heat capacity and isothermal operation of phase-changing boron. As a first step, for example, the boron nitride-coated boron carbide foam discussed by Kennedy and Palmer[1] could be modified into phase-changing boron particles contained and protected by boron nitride. Likewise, the graphite heat storage and exchange system designed for the ISUS RAC[33,34] could also be modified to contain boron-based storage. It is noted that conduction within a foam of spherical particles to ensure even temperature distribution would present a significant challenge. Additionally, boron is known to react with carbon at high temperatures, so directly incorporating boron into the ISUS RAC system would require layering additional materials for compatibility. As a first design, therefore, it is proposed that the graphite thermal storage block, with included channels for heating the flowing propellant, be replaced with boron nitride for chemical compatibility with the propellant[1] and the boron phase change material. This boron nitride structure could be further hollowed and filled with boron to allow for phase change thermal storage; the boron nitride structure and channels would serve to contain the boron, to allow additional thermal conduction throughout the thermal storage medium, and to maintain a barrier between the molten boron and the flowing propellant.

F. Design Summary

Combining all of the above components, a baseline system can be imagined. As a first step, the RAC system pictured in Figure 1 is proposed for further analysis and modeling. Note that the system includes a central core of boron phase change material surrounded by boron nitride. That crucible is insulated with layers of conventional and vacuum insulation. Incoming pre-concentrated solar light enters through the top of the system, as pictured, where a secondary concentrator further focuses the light. Thermophotovoltaics positioned above what is likely to be the hottest surface will convert radiated power to electricity, and a shutter assembly can be used to throttle the system. At this early stage, the means of heat transfer to the propellant has been left out of the design, but can be added in later, either starting from a modification to previous designs (as discussed above) or taking a simulation-suggested design as the heat transfer analysis of the system progresses.

For a high performance microsatellite system in a 100 minute low Earth orbit with 40 minutes in eclipse, a constant electrical draw of 100 Watts combined with a thermal draw of 100 Watts for propulsion is assumed. Allowing for a per-cycle storage efficiency of 75%, and an easily-achieved electrical conversion efficiency of 20%,

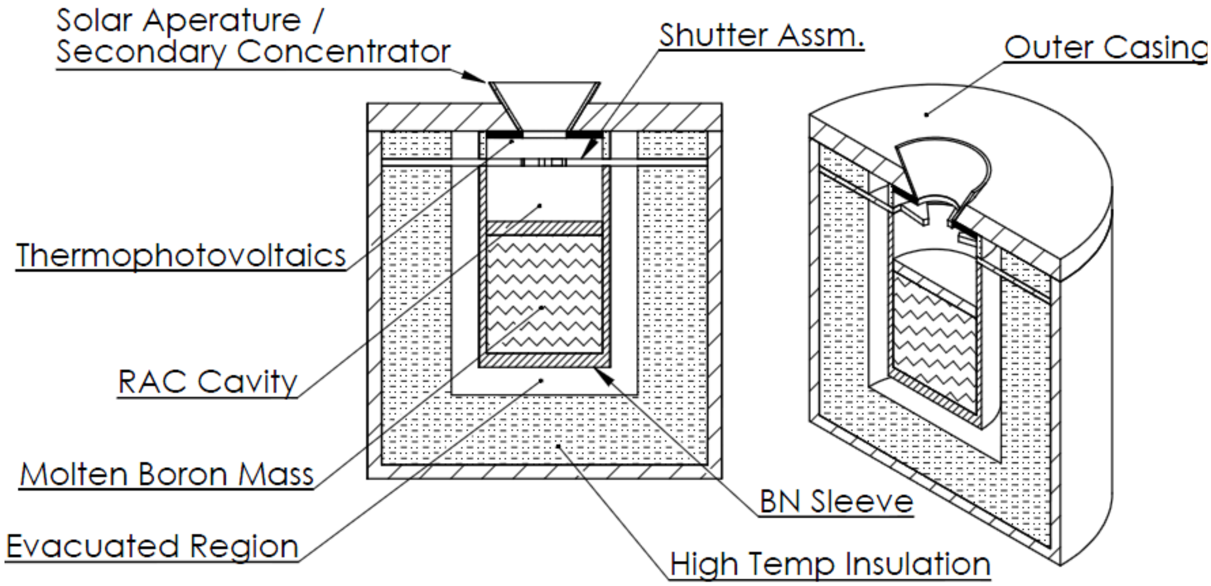

Figure 1. Nominal Design for Receiver/Absorber/Converter Analysis

less than 1/2 kg of boron would be required for energy storage. With a basic insulation design, just over 1 kg of CBCF insulating material would be required; it is assumed that notably less mass would be required with a well designed system combining vacuum insulation and CBCF layers. In this way, an energy density for the storage system of 2-4 times that achievable with conventional lithium ion batteries is likely. Further, assuming a 1360 W/m^2 solar constant, and a 50% efficient solar concentration and collection system (an efficiency likely to be exceeded[17]), just over 2 square meters of solar concentrator would be required, weighing well under a half kilogram[15]. Assuming a reasonable mass level can be achieved with fiber optics used to guide the concentrated solar light, the secondary concentrator, the shutters, and the TPV energy converter, it is likely that the hybrid energy storage system for a high performance microsatellite could have a mass of well under 15 kg, leaving a significant mass budget on board a 100 kg microsatellite for propellant and payload.

For a ground-based system, silicon would likely be utilized in place of the highly expensive boron phase change material. Additionally, due to terrestrial needs, heat exchange would not need to take place directly with the phase change material in order to achieve a useful thermal output; on the contrary, a simple cooling water loop to maintain an ideal TPV temperature could be utilized, producing a useful hot water output for direct use, for space heating, or for other similar purposes. System sizing and designs would vary depending on individual household needs and local climate conditions, but it is noted that 2 kg of silicon would be required per kilowatt hour of storage needed, resulting in a cost of less than $5 per kWh (excluding other system costs). Even budgeting for several days worth of heating and electrical power backup for an average home, the total cost of the silicon storage would be under $1000. Additionally, a well designed concentrator (or system of several concentrators) should be notably less expensive than a large photovoltaic array, and the overall space required for the highly efficient thermal system would be considerably smaller. At the same time, standard PV systems offer little benefit toward the water and space heating requirements in the home. For a terrestrial system, a well designed thermal storage and conversion system should provide significant benefits relative to traditional methods of power generation and storage, combined with significant cost savings.

IV. Experimental Test Facility

In order to develop a practical understanding of the ideas described above, an experimental system is under development at the University of Southern California to physically investigate phase change thermal energy storage coupled with solar concentration. The current system has been designed for the purpose of generating and maintaining molten boron with minimal sample contamination through the use of concentrated solar radiation. This experimental device will then allow for the evaluation of PCM technological requirements in a simulated environment.

A. Materials Considerations and Crucible Design

Elemental boron is highly reactive in both solid and liquid forms as temperatures approach the melting point[35] (approx. 2570 K for amorphous boron[36]). As a result, physically containing boron with minimal contamination in a liquid state is problematic due to its high reactivity with the limited number of materials capable of withstanding the necessary experimental temperatures. A literature review indicated that molten boron has been created in the presence of refractory metals, graphite, and ceramics with varying contamination levels. Since there are few usable high temperature materials available for experimental hardware, it is necessary to understand their properties in relation to a molten boron system.

Refractory metals have been utilized for the construction of effusion cells to create high purity boron thin films via vacuum vapor deposition. In these studies, however, contamination is measured in the thin films produced and not within the bulk boron source; these tests do not specify if the contaminating compounds formed at high temperature might produce a protective layer that prevents further reaction (as in the case of aluminum oxide on aluminum) or whether additional reactions and further material degradation might occur in subsequent tests (as with rust on iron). Therefore, the likely material compatibilities within the USC system must be inferred from experimental data and descriptions.

In effusion cell testing examples, tantalum crucibles have yielded the most promising results,[37] but the purity of films produced using this method has been credited to differing vapor pressures of pure boron and the tantalum boride contaminants within the bulk material.[38] Tantalum begins to form borides as experimental temperatures reach 2300 K,[39] indicating the possibility of contamination once the boron begins to melt. Similar testing utilizing tungsten effusion cells resulted in appreciable contamination of thin films produced with indications that boron is actively attacking the tungsten material.[37] Work performed by Stroms et al. states that tungsten effusion cells will form a protective layer of tungsten boride. However, experimental temperatures in this study did not reach the melting point of boron.[40] Tungsten borides have been formed at temperatures as low as 1700 K.[41] Again, this formation threshold is well below the desired experimental temperature for the phase change system proposed here, and as the melting point of boron is approached, contamination of the bulk may occur. Molybdenum appears to not have been used as an effusion cell material but sample contamination is likely since molybdenum borides become unstable below the desired experimental temperatures.[42] Sample contamination through the reaction of molten boron with refractory metals is likely, and further quantification would require a separate experimental effort. Therefore, refractory metals are not a viable crucible material for the USC system. Nonetheless, the properties of refractory metals make them favorable in other parts of the experimental system and applicability to a future design may be determined after further contamination studies.

In contrast to the available data on refractory metals, work by Stout et al. has evaluated the use of pure graphite as a crucible material with molten boron. In their experiment, molten boron was produced within a graphite crucible and maintained at the melting temperature for approximately 15 minutes. After testing, 22-24% of the boron sample had reacted to form carbide compounds, indicating high reactivity between molten boron and graphite.[43] Contamination was measured after the bulk sample had resolidified and the study states the boron carbides could not

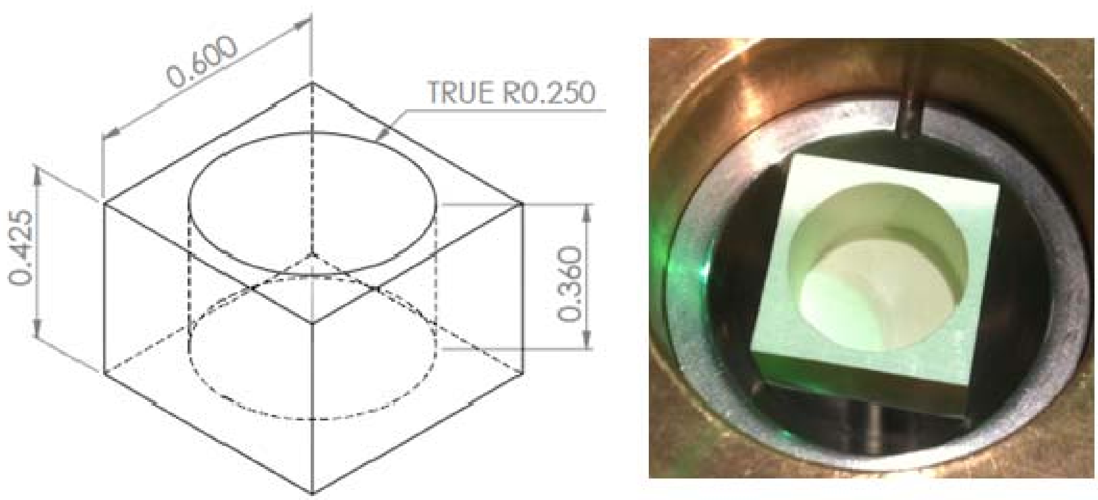

Figure 2. Schematic of the BN crucible design along with a photograph of the crucible resting in the experimental radiation shield with the top section removed.

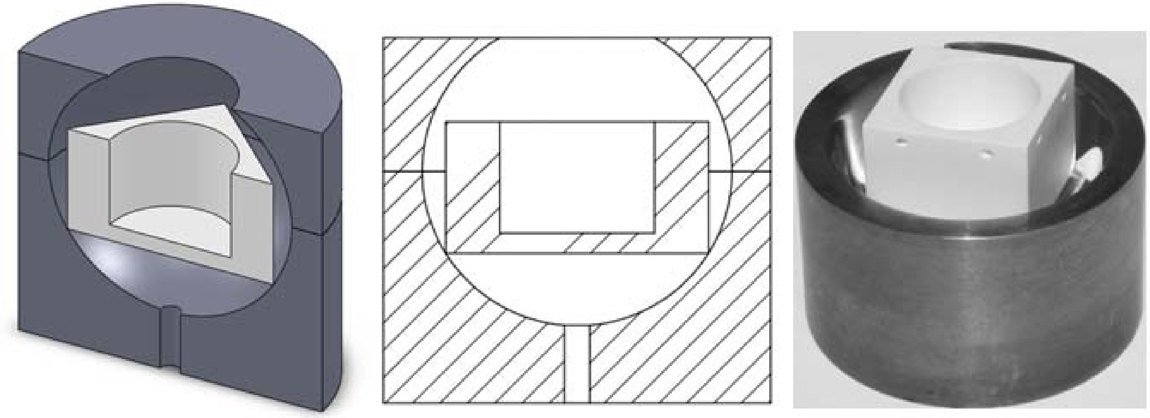

Figure 3. Model Views and Photograph of the BN Crucible and Molybdenum Radiation Shield.

have been in a liquid form during testing due to melting temperatures higher than those achieved during the experiment. This suggests that the solid boron carbide contaminants did not remain affixed to the crucible walls and were circulated through the molten boron mass. Similar testing of solid boron samples below the melting point resulted in negligible contamination, illustrating the increased reactivity of boron after transitioning into a liquid. These results eliminate graphite as a possible crucible material for the experiments to be conducted at USC; however, the high temperature properties of graphite may be useful in a fully developed system.

Due to the contamination issues with graphite and the refractory metals, ceramics are the predominant crucible material suggested in the literature for boron experimentation, with boron nitride (BN) being the most common. Multiple studies have used BN as a container for molten boron, citing negligible contamination of the boron sample,[43-46] which is attributable to BN's low reactivity at high temperatures and a resistance to attack in a boron rich environment. However, additional experimental considerations must be made in the use of BN due to it's strong tendency to disassociate into liquid boron and nitrogen gas at temperatures above 2300 K.[47] Unfavorable disassociation can be eliminated by maintaining a system pressure above the equilibrium pressure of disassociated nitrogen. Data taken by Hildenbrand et al. estimates the required nitrogen overpressure is on the order of $3\text{x}10^{-4}$ Torr at the melting point of amorphous boron. Previous experimental efforts have maintained a suitable operating pressure by operating in inert gas environments, or in the case of Stout et al., by sealing the boron nitride in a graphite vessel and allowing disassociated nitrogen to pressurize the container and prevent further decomposition.

From the considerations above, HBC grade hot-pressed boron nitride crucibles have been selected for the USC system. HBC grade BN was chosen due to the lack of boron oxide binders within the ceramic, which would otherwise require a high temperature bake-out procedure prior to boron contact in order to maintain sample purity. Experimental testing is preformed in a vacuum chamber with a controlled low pressure nitrogen environment to prevent BN disassociation and oxidation of components as well as to mitigate convective heat loss. The crucible, shown in Figure 1, was designed to be 0.6 x 0.6 x 0.425 in (15.2x15.2x10.8 mm) and contain 2 g of powdered boron within a 0.5 in (12.7 mm) diameter, 0.36 in (9.1 mm) deep cylindrical cavity. The cavity design allows incoming radiation to take advantage of boron's relatively high absorptivity as both a solid and liquid and the sharp corners at the edges of the crucible allow for minimal surface contact when installed in the experimental system.

B. Radiation Shielding

At the melting point of elemental boron, heat loss from the uninsulated and unshielded crucible would be dominated by radiation losses. If the loaded crucible is treated as a grey body, radiation losses would exceed 2300 W, necessitating the development of a radiation shield to reduce experimental power requirements. A 1 in (25.4 mm) diameter, mirror-polished, spherical radiation cavity has been designed and constructed as the primary shielding mechanism to reflect and re-radiate energy back to the crucible surface.

As shown in Figure 3, the BN crucible rests within the mirrored cavity surface and maintains minimal contact with the cavity to limit possible conduction losses. A 0.5 in (12.7 mm) diameter hole in the top of the system truncates the spherical chamber and allows for input of concentrated radiation into the cavity while maintaining a view factor approaching unity for the majority of the crucible with respect to the cavity walls. The shield has been machined from molybdenum to take advantage of the high working temperature, chemical resistivity to boron nitride and the ability to effectively polish the cavity surface to a reflectivity greater than 90%. The finished system consists of two sections that allow for disassembly of the shield in order to load the BN crucible. Additionally, a thermocouple port has been included in the bottom of the cavity to facilitate direct contact temperature measurement with the bottom of the crucible. Custom tantalum-sheathed, hafnia-insulated, Type C thermocouples have been developed in conjunction with NANMAC Corporation; the thermocouples have hemispherical tips to further mitigate losses due to conduction down the length of the probe.

Initial theoretical estimates for this radiation shield indicate >70 % reduction in radiation losses at maximum temperature and a required maximum system input power on the order of 800 W. This value has been used to size the associated solar concentration system. However, it is important to note that assumptions made in radiation calculations were purposely chosen to provide an overestimate of radiation losses. Additionally, peak power requirements will occur before the phase transition to liquid boron due to an approximately 30% drop in the surface emissivity of boron when the surface becomes liquid.[48]

C. Solar Concentrating System Design and Construction

Utilization of concentrated solar radiation as the experimental heat source ensures direct correlation of data and techniques with future solar thermal applications. A new solar concentration facility has been constructed at USC consisting of a heliostat, offset parabolic concentrator, and vacuum chamber.

Figure 4 shows a schematic of the general system layout including the use of a first surface redirection mirror to place the focal point of the system within the test chamber. This allows the use of the "top down" radiation shield and crucible as designed above.

The dual axis heliostat, shown in Figure 4, has been refurbished from previous use during AFRL solar thermal testing, and is outfitted with a new 8 ft by 8 ft mirror utilizing aluminum honeycomb panels and replaceable mirror tiles. The heliostat is controlled by an automated tracking system and can also be operated with manual tracking and alignment aided by a shielded video camera and monitor for focal point visualization. Currently, the heliostat provides positional accuracy on the order of 0.3°, which translates to 0.125 inches (3.2 mm) at the focal point. Since the facility is positioned among the buildings of the USC campus, the heliostat is only fully illuminated for approximately 4 hours per day.

Light from the heliostat is directed onto an offset parabolic concentrator taking advantage of an output profile that lends itself to downwards redirection. The lowermost output rays from the concentrator are perpendicular to the ground, allowing all optics within the system to mount above the test chamber and avoid impingement. The concentrator dish has been constructed in a low cost manner utilizing a Prodelin 1194 series fiberglass Ku band reflector. This reflector, as mounted in Figure 5, has a 1.8 m planar cross section and f/d of 0.8. A "slow" dish is required by the redirection geometry and provides a narrow entrance angle for vacuum system integration. This dish has been prepared and mirrorized utilizing the Spectra Chrome process, in which a layer of pure silver is deposited and sealed under a UV protective clear coat.

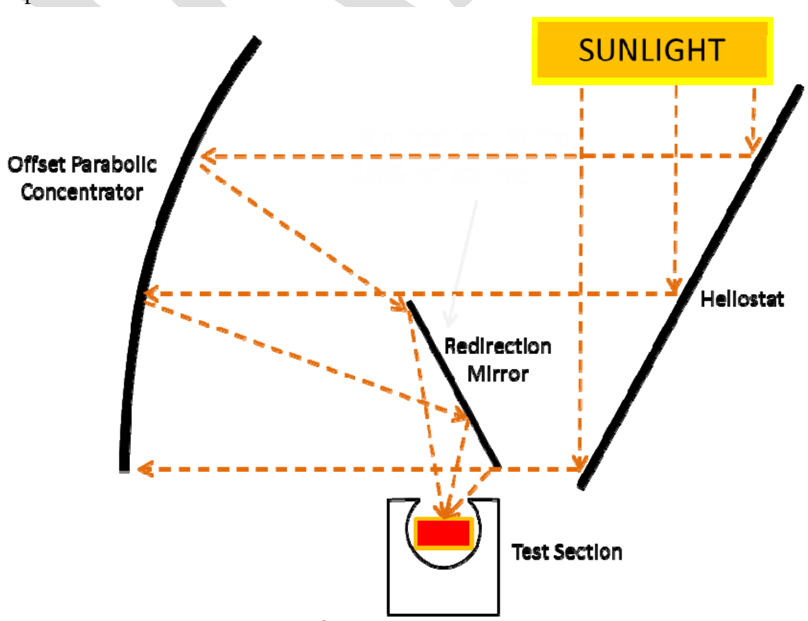

Figure 4. Schematic of the USC Solar Concentration System.

Figure 5. USC Heliostat and 1.8 m Offset Parabolic Concentrator.

After leaving the concentrator dish, solar radiation is redirected via a silvered first surface mirror, through a fused quartz window, and into a vacuum chamber containing the test section. Since the redirection mirror is in the path of incoming radiation from the heliostat, a fraction of the concentrator dish is necessarily shadowed relative to the heliostat. However, the mirror geometry has been optimized to retain 90% utilization of the concentrator dish.

The entire system is sized for effective delivery of 1000 W to the test section at a solar insolation of 700 W/m^2. This value takes into account the reflectivity of all experimental components resulting in an overall transmittance efficiency of 56% from heliostat surface to the surface of the test section.

D. Initial Results

To date, the USC system has operated at 10% system power taken via radiant flux measurements at the focal point. At this low power level, empty BN crucibles have been heated to temperatures over 900 K in order to

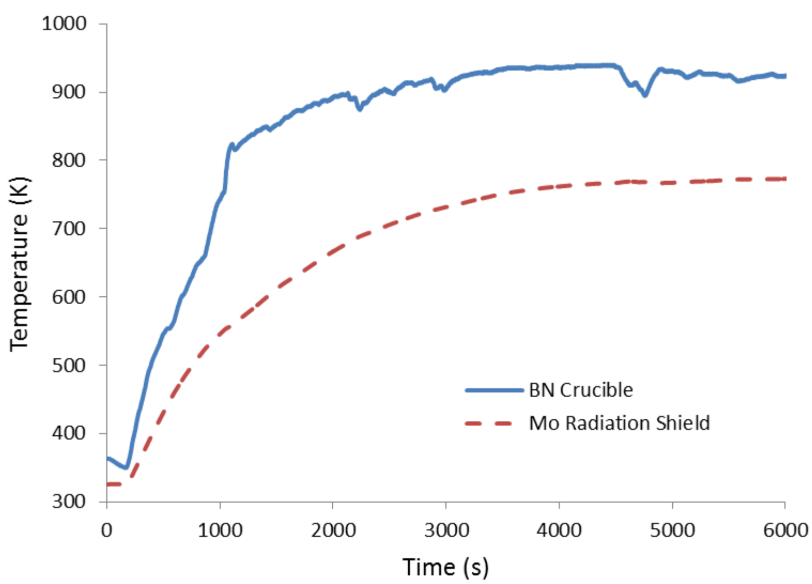

Figure 6. Measured Temperature Trace from Initial Build-Up Phase Test.

evaluate direct contact temperature measurements, heliostat control, and general operation of experimental optics. Figure 6 shows a sample heating profile with a relatively fast crucible heating time. After an extended period, the system approaches thermal equilibrium with the core of the system maintaining a higher temperature than the shielding as expected in the design analysis. Fluctuations in the temperature of the crucible are due to alterations in the heliostat tracking program and switching between manual and automatic tracking mode during the evaluation.

Initial testing data has shown the efficacy of the molybdenum radiation shield in reducing radiative losses from the system. The temperatures reached by test crucibles indicate a minimum 50% reduction in radiative losses with respect to an exposed crucible. This figure is likely to increase as experimental power rises and the polishing techniques for the concave inner surface of the molybdenum radiation shield are refined.

V. Conclusion

A thorough review has concluded that bimodal solar thermophotovoltaic systems employing select high temperature elemental phase change materials for thermal energy storage would yield significant advancements for a variety of solar thermal systems in general and, in particular, solar thermal power and propulsion systems for microsatellites. Silicon was chosen as the near-term phase change material for moderate performance, while the ultimate goal is to develop a high performance system employing molten boron for energy storage. Evaluations of the required components and materials concluded that the basic components required to construct and evaluate a molten silicon thermal energy storage system currently exists, but a significant effort will be required to demonstrate a molten boron system. Assuming these designs can be completed and implemented, a silicon system with hot water output and thermoelectric conversion should result in a highly efficient, inexpensive system for energy production and storage. A boron-based system could provide a low mass, high-efficienty energy storage and propulsion system, enabling very high capability microsatellites in low Earth orbit. An experimental effort is underway at the University of Southern California to evaluate the potential of molten boron phase change energy storage systems, including necessary solar concentration equipment and materials to contain and insulate high temperature molten boron.

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